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Review

A Contemporary Review of Collaborative Robotics Employed in Manufacturing Finishing Operations: Recent Progress and Future Directions

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Abstract

The final phase of the manufacturing process for any artefact involves their surface finishing operations. This phase entails the precise removal of small volumes of material to achieve a specific surface roughness, which is essential for ensuring the artefact's post-production performance and endurance. For certain tooling, such as molds and dies, the finishing operation can be particularly significant, often equating to fifty percent of the total production time and a fifth of the overall manufacturing cost. In recent years, collaborative robotics has come to the fore. These advanced systems allow manufacturers to harness the positive attributes of robots, such as their repeatability, endurance, and strength, while simultaneously leveraging the unique benefits of human workers, including their process knowledge, problem-solving abilities, and adaptability. This co-operation between human and robotic capabilities has opened new avenues for efficiency and precision in the finishing process. This paper investigates the current advancements in collaborative robotic finishing, providing a comprehensive overview of the latest technologies and methodologies. It also highlights existing research gaps that need to be addressed to further enhance the effectiveness of these systems. Additionally, the paper suggests potential areas for future investigation, aiming to drive continued innovation and improvement in the field of collaborative robotic finishing operations.

Keywords: collaborative robotics; Cobot; human–robot interaction; finishing operations; literature review

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1. Introduction

Robots began to be commercially applied to activities such as material transfer, painting, and welding since the 1970s and 80s [1,2]. In the decades since that point in time, two major factors that reinforce the rise of industrial robots are first their increased competence and efficiency and second the falling prices per output produced [3]. However, traditionally, industrial robots are placed behind guards, in cages, and controlled to conduct rapid repetitive operations. This imposes major restrictions on production line space and flexibility in operations. The opportunity for the manufacturer in the Industry 4.0 age [4] is truly bringing the human and robot closer together in production operations. Systems are designed for safety and dexterity, which share the task with the human, in the same workspace. The term for such human–robot operations is colloquially known

as Cobotics [5–7]. A review by Keshvarparast et al. [8] took a holistic look at collaborative robots in manufacturing and assembly systems, while work by Rahman et al. [9] explored Cobotics' foundations/fundamental operations and their alignment with the newly developed Industry 5.0 principles [10]. To date, within the manufacturing domain, Human Robotic Collaboration (HRC) has been applied to five principal areas: 1. Palletizing and packing [11,12]; 2. Welding and joining [13,14]; 3. Component assembly [15,16]; 4. Bulk material handling [17–19]; 5. Quality and inspection [20–23]. Cobotics have shown themselves to be effective across a complete range of manufacturing operations and are aiding industry in the support of the Smart factory of the future [24].

Examples of repetitive operation in the manufacture of products include finishing, buffing, and polishing. Such processes are applied to improve the surface or sub-surface functions beyond the degree accomplished in preceding manufacturing processes, subtractive or additive machining, bulk forming, etc., such as polishing operations of features in molds and dies [25]. They improve quality and service life, thereby enhancing product quality produce from their operation. Other typical component examples are shown in Figure 1. They are generally categorized under the headings of lapping/polishing; grinding; honing; magnetic abrasive finishing; coated abrasives and superfinishing employing abrasive stone, belt, or tape [26]. The abrasive grit and their construction in polishing disc, grinding belts, and compounds are governed by specific standards (FEPA Standards 42-1:2006 [27]) and (ISO 8486 [28]).

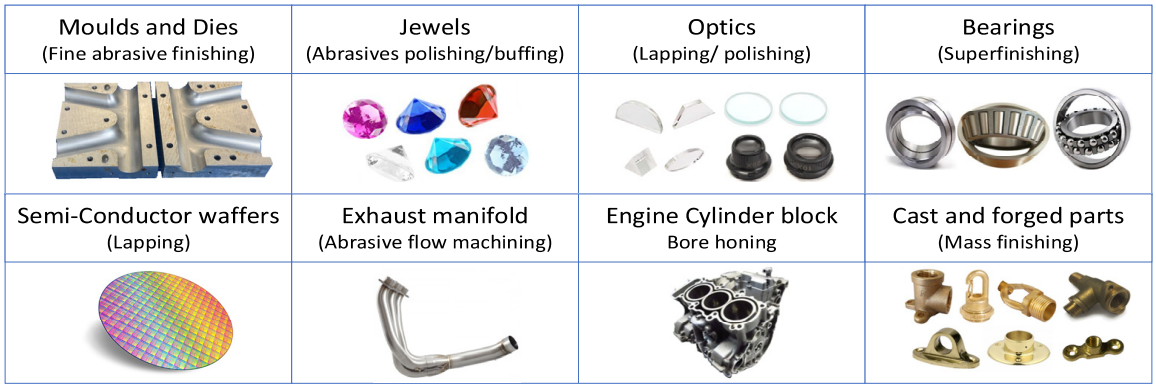


Figure 1. Typical products and finishing operations.

The application of robotics to finishing is nothing new [29]. The repeatability of the robot means it is ubiquitously applied to products, turbines [30], steel molds [31], plumbing artefacts such as sink levers, faucets, etc. [32]. This process relies mainly on uniform metal removal rates, with open loop control systems following paths generated from computer-aided design and computer-aided manufacturing software [33,34]. Table 1 lists some of the most recent reviews and surveys in manufacturing that are also relevant to finishing operations. For example, Ke et al. [35] produced a review of the specific technologies, the integration of robots with various polishing techniques and the status of constant force control in robot-assisted polishing, although there is no specific focus on collaborative (such as human factor) issues. Deng et al. [36] produced a review of robot grinding and polishing force control modes. Much of the work in these two studies extends beyond the collaborative phase and focusing on fully robot conducted processes.

Table 1. Previous surveys on collaborative systems.

Paper	Context of Review
Ajoudani et al. (2018) [37]	Interfaces for robots' interactions in collaborative systems.
Villani et al. (2018) [38]	Barriers and applications of Cobots in manufacturing systems.
Li et al. (2018) [29]	A review of robotic polishing.
Bragança et al. (2019) [39]	An overview of how collaborative robots can be used to support human workers in Industry 4.0 manufacturing environments, concentrating on the human perspectives and safety.
Matheson et al. (2019) [40]	Interaction types between humans and robots in collaborative manufacturing systems.
El Zaatari et al. (2019) [41]	An overview of collaborative industrial scenarios and programming requirements for Cobots for implementation.
Hentout et al. (2019) [42]	A literature review of research and development on human–robot interactions in industrial collaborative robots (between 2008 and 2017)
Knudsen and Kaivo-Oja (2020) [43]	Presentation of an overview of current collaborative trends and futures frontiers of the Cobot development with particular emphasis on the role of Cobots within the Industry 4.0 paradigm.
Hashemi-Petroodi et al. (2020) [44]	Current issues in manufacturing, dual resource constrained (DRC), and human–robot collaboration (HRC) optimization.
Vicentini (2020) [45]	Terminology in safety of collaborative robotics.
Proia et al. (2021) [46]	Control techniques for collaborative robotics in industrial settings.
Gualtieri et al. (2021) [47]	Human–robot safety and ergonomics in collaborative systems.
Pinheiro et al. (2022) [48]	Safety and ergonomics/human factors for industrial collaborative robotics.
Javaid et al., (2022) [49]	Implementations and applicability of Cobots in industrial manufacturing scenarios.
Kóczi and Sárosi, 2022 [50]	Review of the major elements of safety in the application of collaborative robots.
Deng et al. (2022) [36]	Review of force control strategies for robotic grinding and polishing.
Ke et al. (2023) [35]	Review of robot-assisted polishing, specifically the integration of robots with various polishing techniques.

The purpose of this paper is to critically review contemporary Cobotics knowledge applied to current finishing processes, identify the research gaps, and propose solutions to bridge them. Thus, the primary research questions for this review include:

RQ1: What is the current status of Cobotics in finishing operations?

RQ2: What are the main problems identified by researchers?

RQ3: What studies have been conducted on the role of humans in Cobotics?

RQ4: What are the primary challenges that hinder the implementation of Cobotics in finishing operations?

According to the above research questions, a literature search was performed to extract all papers (including journal articles, conference papers, book chapters, and PhD dissertations) related to collaborative robotic finishing. Web of Science, SCOPUS databases, and Google Scholar were used. Suitable keywords and Boolean operators ("Collaborative robotic finishing" OR "Collaborative robotic polishing" OR "Collaborative robotic manufacturing" OR "robot–human collaborative manufacturing" OR "Cobots in manufacturing") OR ("Cobots safety" OR "robotic safety") were used, with the most recent update in February 2025. To keep the review contemporary and to avoid duplicating existing surveys, a

cut-off year of 2017 was set for the collaborative finishing operations research, although earlier works were included when relevant for background or contextual reference. In addition, four exclusion criteria were set: (1) Papers written in non-English language; (2) Papers that are not focused on finishing operations, such as assembly line, packaging, etc.; (3) Papers that are focused on non-technical issues, such as government policy, document management, etc.; (4) Systematic reviews, user guidelines, etc. Finally, a total of 67 papers were chosen in this review.

The remainder of the paper is structured as follows. Section 2 provides a review of the most recent research in collaborative polishing operations. Section 3 provides a discussion of the existing knowledge and potential areas that are still needed in investigating to truly achieve collaborative polishing. Concluding remarks are provided in Section 4.

2. Human–Robot Collaboration for Finishing Operations

Although many forms of automation have been applied to sectors in need of finishing operations, it is still mainly conducted manually [51–55]. Compared to traditional robots, Cobots offer several advantages: (1) Better worker safety: This human style of finishing typically involves a highly skilled and trained worker in an un-healthy environment due to exposure to dust, particulates, and noise pollution [56] as well as the vibrations from the handled tooling [57]. Prolonged manual finishing processes increase the possibility of musculoskeletal diseases (MSDs) such as vibration white finger or other severe injuries [57,58]. Cobots potentially shift the work of the human from a dull, dirty, and dangerous process to the cognitively more demanding part of inspection and process strategy definition [59]. (2) Space efficiency: As Cobots are designed to work alongside humans in the same workspace, they are generally smaller in size and more easily integrated into existing production lines, even in small workspaces. (3) Ease of use: In general, Cobots are more easily programmed and set up, and therefore they can be applied on a broader user base, such as smaller and medium-sized businesses. (4) Lower cost: From a financial perspective, Cobots are much cheaper in comparison to the industrial robots due to low cost and high flexibility, which generate return on investment much more quickly than other industrial robots. Overall, health issues, relative scarcity of skilled finishing workers through aging and people leaving the sector [60], compactness, accessibility, and competition with low-cost global production areas are the reasons why robotic and Cobotic solutions are currently being sought [61]. With this in mind, the forecasted market value (USD) by 2030 for Cobots is expected to be USD 11.8 billion, a 35.2% compound annual growth [62]. Recent progress in the area of collaborative robotics applied or utilized for finishing operations is still concentrated on the objectives of better quality, greater efficiency, and safety, and it can be classified into four themes: operation parameter setting and control, tool path planning and trajectory generation, human factors, and safety frameworks for collaboration. Recent research in these areas is explored in the following sections.

2.1. Operation Parameter Setting and Control

One of the key issues for Cobotics in finishing operations is whether they can achieve surface roughness as good as manual operators. In the Preston method [63], for all the fine abrasive polishing, sanding and belt grinding, the material removal rate is related to spindle speed, feed rate, positive contact pressure, and contact surface area. These factors then correlate to the surface finish [64] after each cut path. Thus, for the Cobotics finishing operation, first, appropriate operation parameters need to be identified based on the required surface roughness; second, proper control of operation variables is enabled according to certain circumstances during the process.

In early works by Kalt et al. [56], an approach was developed to capture polishing parameters and operational variables of manual polishing processes. Experiments were conducted on complex aerospace components. The goal was to understand what machining parameters are controlled by manual operators and when and under what circumstances the operators reconfigure the machining variable to obtain the surface quality needed. Data were later used in the development of an automated polishing system [65]. In Orchoa and Cortesao [66], the authors proposed a torque-based impedance control architecture for robotic-assisted mold polishing based on taught human skills. A cartesian impedance control referenced to the end-effector frame with posture optimization was proposed to tackle this activity. Human parameters were captured, analyzing position and force patterns. These were later replicated by the robotic system. Lin et al. [67] designed a grinding tool used with a six-axis industrial manipulator (TM5-700). It aimed to achieve better grinding quality through actively controlling the contact force. Ubeda et al. [68] explored the potential of the new generation of collaborative robots finding that in comparison with current industrial robots, collaborative ones can perform the same fine abrasive finishing task with comparable results. Specifically, the applied force does not guarantee a better surface finish. A similar finding was presented in Wang et al. [69], although feed rate was shown to present a better opportunity for increased productivity. Li et al. [70] produced a predictive model for the end surface finish of robotic polishing based on contact force, rotational speed, feed rate, sandpaper grit, and initial surface quality. The optimization parameters for polishing the end surface of chalcogenide glass fiber connections were studied by Guo et al. [71]. The best polishing parameters were identified by analyzing the impact of various polishing parameters on the quality of the fiber end surface, including particle size, grinding speeds, and polishing durations. The completed ChG fiber end surface was free of spots, fractures, and scratches, with a surface roughness of 48 nm. This demonstrated that the optimal polishing parameters could lower the connector's average insertion loss to 3.4 dB. Zhang et al. [72] examined how process factors affect surface temperature, temperature gradient, and scanning direction temperature distributions. They also provided an analysis of the effects of the parameters on these variables. For hybrid metal matrix composite materials, Rahi and Dubey [73] employed a Response Surface Methodology for experimental modelling, response prediction, and optimization. A genetic algorithm was used for optimizing the response variables. The optimization goal was material removal rate as well as surface roughness. In Mitropoulos et al. [74], a prototype polishing jig that offers elementary force control capability was utilized in order to perform flat metal surface polishing experiments based on trochoid toolpaths. A Taguchi approach was employed to fine-tune the experiments to optimize polishing speed, feed rate, and force levels for the roughness of the polishing surface. Wang et al. [75] employed a similar process propeller finishing for optimizing belt grinding parameters: abrasive grain size, grinding speed, feed rate, and grinding depth. Ramesh-Kumar and Omkumar [76] applied the same approach for soda glass polishing including parameters of speed, slurry flow rate, down pressure, and process time. Hahnel et al. [77] employed the SYMPLEXITY approach combining both a collaborative intelligence-based and a cooperative human–robot-based technological approach. The same approach was later employed by Ferraguti, et al. [78] and Pini and Leali [79] to explore the abrasive finishing of molds and dies. An objective metrology surface qualification device was introduced for surface quality assessment. With the integration of the robot-based polishing and measurements, an initial parameter set-up was generated.

Nguyen [80] employed a UR5 Cobot and an intelligent system for sand operations. Using fast Fourier transforms (FFTs) [81] of the forces, correlations between the sanding frequency and the amplitude with the surface roughness were measured. The velocity of

the sanding head is adjusted based on the roughness of the material being processed. For a stable force tracking, Li et al. [82] demonstrated the use of variable impedance control methods for the system damping and stiffness for the robotic grinding and polishing experiments of blades from aircraft engines. A similar approach was also demonstrated by Huang et al. [83], also on turbine blades. In automotive production, Perez-Vidal et al. [84] developed a collaborative tool for robotic polishing in order to allow the simultaneous operation of the robot system and human operator to cooperatively conduct the polishing task. For this purpose, the implementation of the tool using the minimum viable product approach was obtained. Furthermore, a robust hybrid position-force control was proposed to use the developed tool attached to a robot system, and some experiments were conducted to show its performance. In Solanes et al. [85] and later elaborated in Gracia et al. [86], an approach was explored of robots for surface polishing through hybrid position-force control based on task priority and adaptive non-conventional sliding mode control. Vaidyanathan and Lien [87] proposed for a robot and human to cooperatively perform surface finishing tasks, polishing, grinding, and deburring. They used a Swayer Cobot with two force sensors attached to the end-effector and tool, one for the surface processing task and the other for use by the operator to guide the robot tool. For grinding of complex unknown profiles, the authors of [88] developed a constant force control and proposed human–robot collaboration. Combined with a HRC activity, their method enabled the robot to be guided by a human to start the grinding process from arbitrary positions of the unknown workpiece contour. Results showed improved grinding surface quality and time reduction against the benchmark. Devine et al. [89] developed a process model and control strategy for teleoperation that ensures constant material removal depth along the sanding path.

The above works are summarized in the following Table 2.

Table 2. Works on operation parameter setting and control for HRC.

Paper	Main Topics	Robots	Materials
Kalt et al. [56]	Capturing polishing parameters of manual polishing processes	KUKA KR16	Complex aerospace components
Orchoa and Cortesao [66]	A torque-based impedance control architecture for robotic mold polishing	Franka Emika	Steel mold
Lin et al. [67]	A grinding tool with contact-force control	TM5-700	Workpiece (100 mm × 100 mm × 2 mm)
Ubeda et al. [68], Wang et al. [69],	That applied force does not guarantee a better surface finish	Robot UR3	Aluminum, steel, brass, wood, plastic
Li et al. [70]	A predictive model for robotic polishing	Nachi industrial robot	Stainless steel workpiece
Guo et al. [71].	The optimization parameters for polishing	ULTRAPOL-1200	End surfaces of ChG glass fiber
Zhang et al. [72]	The influence of process factors for surface temperature, for electron beam surface polishing	ANSYS Parametric Design language	Metal surface
Rahi and Dubey [73]	A Response Surface Methodology for hybrid metal matrix composite materials	ELECTRO-M	Hybrid metal matrix composite
Mitropoulos et al. [74]	Optimizing polishing speed, feed rate, and force levels		Flat metal surface Al-SiC-Gr composite
Wang et al. [75]	Optimizing belt grinding parameters	a five-axis CNC belt grinding	Large marine propeller (manganese bronze)

Table 2. *Cont.*

Paper	Main Topics	Robots	Materials
Ramesh-Kumar and Omkumar [76]	Optimized parameters of speed, slurry flow rate, down pressure and process time	Chemical Mechanical Polishing	Soda lime glass
Hahnel et al. [77]	Combining both a collaborative intelligence-based and a cooperative human–robot-based technological approach.	Autodesk "PowerMill Robot"	Two plates
Ferraguti et al. [78], Pini and Leali [79]	Surface quality assessment for the Abrasive Finishing	IRB 4600 ABB robotic	Pre-hardened steel flat plates, type 1.2738
Nguyen [80]	A Cobot and an intelligent system for sand operations	UR5e	Wood and metal panels
Li et al. [82], Huang et al. [83]	Variable impedance control methods for the robotic grinding and polishing	UR5e	Turbine blades
Perez-Vidal et al. [84]	A collaborative tool for robotic polishing with a hybrid position-force control	UR5/UR10	Horizontal flat surface
Solanes et al. [85], Gracia et al. [86]	A hybrid position-force control of robots for surface polishing with task priority	Sawyer Cobot	Flat object
Zhao et al. [88]	A constant force control and human–robot collaboration for grinding	.	Complex unknown profiles
Devine et al. [89]	A process model and control strategy for constant material removal depth along the sanding path	Yaskawa HC10	Fat 3D printed ABS test articles

2.2. Tool Path Planning and Trajectory Generation

Tool path is crucial for surface roughness, the uniform surface quality, and production efficiency. Thus, path planning and the following trajectory generation are another key issue for Cobotics on finishing operations.

Kana et al. [90] and Lakshminarayanan et al. [91] proposed a collaborative framework where the robot assists an operator to guide the end-effector/tool along a pre-defined parametric curve. The algorithm was demonstrated in two scenarios. In the first case, the authors addressed a collaborative chamfering task, whereas the second case focused on a polishing application (for straight edges). For these kinds of tasks, the curve to be traced assumes the shape of a straight line along the edge. The authors made use of the compliant feature of a Cobot, which allows the user to physically guide the robot in the task space to generate a mathematical model for the tool path. From the end-user perspective, this is more intuitive than the classical programming-based path planning approaches. In Mohsin et al. [92], a tool path planning algorithm with controlled force and polishing parameter optimization was developed to perform a polishing operation using a robot arm holding the workpiece that was being polished by an external passive polishing tool. For sanding of glass fiber turbine blades for defect removal, Oubre et al. [93] employed a collaborative robotic system equipped with a vision system. Path planning for the sanding was developed based on a travelling salesman problem, with the centroid of each of detected defected areas representing the node that the robotic arm has to visit. The optimization was conducted using a simple 2-Opt algorithm [94]. A region-based approach for toolpath planning to avoid gouges was proposed by Xie et al. [95] for the belt grinding of complex parts. The work included algorithms of gouge analysis and an automatic selection of a compatible belt grinding mode.

An approach with control points of NURBS (Non-Uniform Rational B-Splines) for path planning was employed by Su et al. [96] for the grinding finish of water facets. During the grinding process, the robot trajectory could be adjusted to avoid a possible collision with the operator and robot. Their approach allowed for two or more humans in the same workspace. For both coexistence and collaborative workspace usage, Maric et al. [97] presented an HRC for delicate sanding of complex shape surfaces using a standard industrial manipulator. For coexistence work, a CAD model was used for path planning; for collaborative work, the manipulator was equipped with the force/torque sensor and bespoke design-compliant control algorithm. The force sensors were used to assist control and discuss trajectory planning employing a KUKA KR10 robot for the work.

Liu et al. [98] proposed a virtual design scheme of dual-industrial robot collaborative polishing workstation using vehicle wheel hub polishing as the object of the research and aimed at the difficult problem of trajectory planning and automatic production coordination of its inner hollow-out polishing. Early work by Rozo et al. [99] proposed a framework for a user to teach a robot collaborative skills from demonstrations. Specifically, the authors presented an approach that combined probabilistic learning, dynamical systems, and stiffness estimation to encode the robot behavior along with the task. This allowed the robot to learn trajectory following skills and required forces. In Lin and Wahyudi [100], the authors developed a haptic-based robot teaching tool for coexistent HRC to generate a skillful trajectory for wooden furniture polishing, with the haptic sensing the skilled worker motions. These were then employed to develop teaching methods for the robot to allow a skilled operator to monitor the process and the condition of the surface aircraft interior panels in a coexistent workspace.

Forlini et al. [101] presented the automation of shoe polishing using a Cobot, beginning with the creation of polishing trajectories and applying them to starting from the design of polishing trajectories, implementing them on a UR5e system, controlling the contact force of the tool, and performing toe shoe polishing. The work was further expanded in [102], where the authors proposed a three-tier approach for trajectory generation and its replication by the robotic arm to accomplish handcrafted shoe polishing consisting of manual path recording by a qualified operator using the robot. The second approach combines the manual path recording with a CAD/CAM system for trajectory optimization. Finally, the last method is based fully on the CAD/CAM digital data for automatic trajectory generation. Zanchettin et al. [103] introduced a real-time trajectory optimization method based on a genetic algorithm and a Digital Twin (DT) for collaborative robots. The optimization is employed to assess the optimal robot trajectory that simultaneously minimizes the risk of collision with the human operator and the trajectory traversal time. The volume of the collaborative workspace employed by the robot's trajectory is simulated within DT.

Table 3 lists the works on tool pathing planning and trajectory planning for HRC.

Table 3. Works on tool path planning and trajectory planning for HRC.

Paper	Main Topics	Robots	Materials
Lakshminarayanan et al. [91], Kana et al. [90]	User physically guides the robot to generate a mathematical model for the tool path	LBR IIWA 7	Hard metals (aluminum)
Mohsin et al. [92]	A tool path planning algorithm with controlled force and polishing parameter optimization	ABB IRB 1200	Curved surfaces (eyeglass frame)
Oubre et al. [93]	Path planning for the sanding based on a travelling salesman problem	UR5e	Fiber glass panels, wind blades

Table 3. *Cont.*

Paper	Main Topics	Robots	Materials
Xie et al. [95]	A region-based approach for toolpath planning to avoid gouges for the belt grinding of complex parts	ABB IRB 4600 robot	Milled faucet made of copper
Su et al. [96]	Path planning with control points of NURBS for the grinding finish of water facets	Robot of Googol Technology Ltd.	Water taps
Maric et al. [97]	CAD model for path planning and control algorithm with force sensors for trajectory planning	Kuka KR10 i	Complex shape surfaces
Liu et al. [98]	A virtual design scheme of robot collaborative polishing workstation for the problem of trajectory planning	Dual-industrial robot	Automobile wheel hub
Rozo et al. [99]	Approach with probabilistic learning for the robot to learn trajectory following skills and required forces.	WAM robot and Kuka LWR	
Lin and Wahyudi [100]	A haptic-based robot teaching tool to generate a skillful polishing trajectory	Fanuc M20-iA/35M	Wooden furniture
Forlini et al. [101]	Creation of trajectories for the automation polishing using a Cobot	UR5e	Shoe leather
Forlini et al. [102]	A three-tier approach for trajectory generation for shoe polishing	UR5e	Shoe
Zanchettin et al. [103]	A real-time trajectory optimization method based on a genetic algorithm and a Digital Twin (DT) for collaborative robots	ABB YuMi dual-arm robot,	Small parts

2.3. Human Factors

While the majority of the work considers robots' actuations against a predefined task with the human providing the flexibility to enable collaboration, some researchers have started investigating how characteristics of the human need to also drive the robots' activities.

Maceira et al. [104] found that for effective human–robot collaboration, robots need to predict and most importantly respond in real time to the worker's intentions. The authors developed a recurrent neural network-based algorithm to recognize worker force information during a collaborative activity. This could then be used to detect human intentions on other collaborative tasks. In a step towards collaborative robotics, Olivares-Alarcos et al. [105] followed a similar path with their development of a robotic system that is able to identify intentions of different humans and to adapt its behavior consequently based on measured force data.

In Hopko [106], the author used metal surface polishing to examine the operator fatigue, sex, and robot assistance level, all highly relevant and interrelated factors for optimizing human–robot collaboration system designs with respect to task performance and user experience. The findings indicated that assistance through high automation significantly improves task accuracy and efficiency but does not change precision, whereas fatigue impacts task efficiency but not accuracy or precision. In Pearce et al. [107], the authors proposed an optimization framework that generates task assignments and schedules for a human–robot team with the goal of improving both time and ergonomics and demonstrated its use in six real-world manufacturing processes that are currently performed manually. Using the strain index method to quantify human physical stress, they created a set of solutions with assigned priorities on each goal. The resulting schedules

provide engineers with insight into selecting the appropriate level of compromise and integrating the robot in a way that best fits the needs of an individual process. In Kim et al. [108], the authors proposed a method by a user study that involved a human–robot collaboration task, where the subjects ran a polishing machine on a part that was brought to them by the collaborative robot. Within the framework, the human overloading joint torques were estimated and monitored online using a whole-body dynamic state model. This provides the manufacturer with the option to enable ergonomic and task-optimized human–robot collaboration through optimizing to minimize the overloading joint torques. In Chiriatti et al. [3], the authors presented a simulation-based approach to evaluate a collaborative robotic system for leather shoe polishing. This resulted in the reduction in manual labor by limiting it to the finishing stage of the process, where the aesthetic result is fully achieved, and the phase that uses the adaptability of the human is brought to the fore. Thus, ergonomics of the operator were improved. Meanwhile, the influence of process parameters and design solutions indicated that future development could be made with tooling changes specifically for robots rather than humans as in the initial situation. In Lamon et al. [109], the authors developed a method where the robot's physical behavior is adapted online to match the human motor fatigue. The robot starts as a follower and imitates humans. As the collaborative task is performed under the human lead, the robot gradually learns the parameters and trajectories related to task execution. The robot monitors human fatigue during the task production. When a predefined level of fatigue is indicated, the robot uses the learned skill to take over physically demanding aspects of the task and lets the human recover some of the strength.

Wang et al. [110], later expanded in Wang et al. [111], investigated the process optimization of a cooperative work environment for polishing molds. The authors found that the robot was only capable of polishing a proportion of the mold features and the human needed to complete the task. With this in mind, an optimization approach based on an analytic hierarchy process (AHP) and a genetic algorithm to support the robot's choice of tool and feature sequence was presented. For coexistence robotic collaboration, Tsarouchi et al. [112] proposed an approach that allocates tasks based on robot capabilities. The intelligent decision-making approach was implemented in a Robot Operating System (ROS) framework, where body gestures were used for interactions and commanding the robot. For general finishing tasks, Girbes-Juan et al. [113] identified that potential high inaccuracies of the product tasks require both human adaptability and robot accuracy for success. For standard and coexist workspaces, the authors developed a multi-modal teleoperation system combining haptics and an inertial motion capture system employing a Baxter dual-arm collaborative robot. The human operator feels the sense of touch via haptic feedback, while using the motion capture device allows more naturalistic movements. A visual feedback assistant was also developed to enhance immersion. Testing showed the overall task time was reduced in comparison to standard operation. For laser polishing, Gaz et al. [114] proposed a control algorithm that is able to distinguish the external torques acting at the robot joints in two components: one due to the polishing forces being applied at the end-effector level, the other due to the intentional physical interaction engaged by the human. The latter component is used to reconfigure the manipulator arm and accordingly its end-effector orientation.

Paxton et al. [115] found two main problems with existing systems for programming Cobots: First their clumsy user interfaces, and second their inability to perceive the world in ways that are meaningful to humans. Within these three key characteristics is a key to a system for authoring robot task plans, capability, usability, and robustness. The authors designed COSTAR, a Behavior Tree-based system, to create task plans for industrial robots to take these characteristics into consideration. The tool was demonstrated on

surface polishing, wire bending, and assembly activities. Ren et al. [116] used a force interaction method as natural command communication to build a teaching playback strategy for robots. It allowed the human workers to easily guide robots to perform finishing operations directly affecting the position of the robot with their hands without deactivating the servo motors, generally through a 3D Mouse, joystick, or pendant. This is especially useful for robotic arms with axes that can be easily affected by gravity and would usually require power to maintain their position [117]. The PbD (Programming by Demonstration) is an online programming approach where a human performs a task manually; in parallel, the robot is observing, following, and learning demonstrations in real time [118]. The main advantage is that PbD allows accelerating programming tasks and reducing the learning difficulty of robot programming by just demonstrating the operation sequence [119]. Ge [119] was one of the first to demonstrate a PbD approach with an optical tracking system and ABB YuMi dual-arm robot. The human co-worker demonstrated the task to be conducted, and the operator arms motions were transferred to Cobot and generated the robot program automatically. Early work by Restrepo et al. [120] presented a structured PbD approach allowing the human co-worker to program and locally modify the virtual guides through physical interaction with the Cobot. To overcome the knowledge gap in programming Cobots, Halim et al. [121] implemented a hybrid approach combining intelligent computer vision and voice control capabilities. Using a vision system, the human is able to transfer spatial information of a 3D point, lines, and trajectories using hand and finger gestures. The voice recognition system further assists the user in parametrizing robot parameters and interacting with the robot's state machine. In De Franco et al. [122], the authors proposed a simple and intuitive interface exploiting the emergent Augmented Reality (AR) technology. Their interface aims not only to enhance human awareness of the robot status and planned actions during collaborative tasks, but also to improve the quality of the work. The presented interface enables the human operators to interact with the system sending commands (gesture or vocal) and receiving instant feedback (holograms and sound) through an AR device, enabling an intuitive way to coordinate HRC polishing. In order to achieve synergy between the operator and the robot, a collaborative robot was built for surface sanding task by García Fernández [123]. Bimanual robot teleoperation was conducted through an AR-based interface integrated with control algorithms, including Sliding Mode Control (SMC) and priority-based control.

In addition, for effective collaboration, the robot and the human need to be trained together [124]. This is particularly relevant for human operators who lack a clear understanding of the robot's power, speed, learning methods, and communication capabilities, or who simply do not trust robots as fully capable teammates [125]. Gavriushenko et al. [124] addressed the importance of training for HRC and pointed out that both human pedagogy and the approaches used in machine learning could benefit in this task.

Table 4 shows the list of the works related to human factors in HRC.

Table 4. Works on human factors in HRC.

Paper	Main Topics
Maceira et al. [104]	A recurrent neural network-based algorithm to recognize worker force information and detect human intention
Olivares-Alarcos et al. [105]	Identification of intentions of different humans and adaptation of behavior consequently based on measured force data
Hopko [106]	Examination of operator fatigue, sex, and robot assistance level for metal surface polishing by HRC
Pearce et al. [107]	An optimization framework for task assignments and schedules of a human–robot team aiming to improve both time and ergonomics

Table 4. *Cont.*

Paper	Main Topics
Kim et al. [108]	Ergonomic and task-optimized HRC for minimizing the overloading joint torques
Chiriatti et al. [3]	A simulation-based approach to evaluate a HRC for leather shoe polishing so as to reduce manual labor
Lamon et al. [109]	A method to adapt the robot's physical behavior online to match the human motor fatigue
Wang et al. [111], Wang et al. [110]	Identification of the mold features that need a human to complete and optimization of polishing operation scheduling
Tsarouchi et al. [112]	A Robot Operating System (ROS) framework using body gestures for interactions and commanding the robot
Girbes-Juan et al. [113]	A multi-modal teleoperation system combining haptics and an inertial motion capture system for a dual-arm collaborative robot
Gaz et al. [114]	A control algorithm for laser polishing to distinguish the external torques on the robot joints into polishing forces or the intentional physical interaction engaged by a human
Paxton et al. [115]	COSTAR, a Behavior Tree-based system to create task plans for industrial robots in consideration
Ren et al. [116]	A teaching playback strategy for robots using a force interaction method as natural command communication
Restrepo et al. [120]	A PbD approach for humans to program and locally modify the virtual guides through physical interaction with the Cobot
Halim et al. [121]	A hybrid approach combining intelligent computer vision and voice control capabilities to program Cobots
De Franco et al. [122]	An interface for HRC polishing for operators sending commands by gesture or vocal signal and receiving feedback by an AR device
García Fernández [123]	An AR-based interface integrated with SMC and priority-based control for surface sanding
Gavriushenko et al. [124]	Training both the robot and the human together for HRC

2.4. Frameworks for Cobotic Safety

When putting robots into the same workspace as humans, Lasota et al. [126] identified two potential ways the system could injure a human. First, physical injuries are caused by unwanted contact between humans and robots. Second, indirect or psychological injuries are caused by many factors such as the robot's posture or motion characteristics. The first law of Asimov's, "Three Laws of Robotics", is defined as follows: "A robot may not injure a human being or, through inaction, allow a human being to come to harm" [127]. This means that safety is the foremost consideration factor in any case. Much of the earlier work looked at the post-collision phase of HRC, with works looking to limit the maximum energy of the impact [128], enabled by light weight [129,130] or compliant structures or actuator [131,132] or by using the measured force [133–135].

The works of Vido and Pancchini [136] presented a conceptual safety system architecture that is especially useful for covering safety requirements during the early design stage of a collaborative workstation specifically to reduce safety risks to humans. Zanchettin et al. [6] proposed metrics for safety evaluation in human–robot collaborative manufacturing environments. These metrics are derived from the working distance between the human and the robot. From these, a control strategy that regulated the velocity of the robot on a given path/trajectory was developed. In the work by Su et al. [96], the region in which the operator and the robot arm do not collide was identified through tracking the operator's motion. The grinding trajectory is modified according to possible collision predicted. There are numerous sensors used to produce robust detection and tracking of the pose of the operator, mostly based on RGB-D [137]. Wang et al. [138] produced a closed-loop system structure using an RGB camera to capture the color video frames and a depth camera with

a built-in scanner which senses the depth of the shooting scene. The approach combined with multiple collision detection algorithms was deployed to identify a suitable solution for specific HRC tasks. For Magrini et al. [139], the safety of the human was the main concern. They developed a framework for ensuring human safety in a robotic cell that allows human–robot coexistence and dependable interaction. The framework is based on a layered control architecture that exploits an effective algorithm for online monitoring of relative human–robot distance using depth sensors. This method allowed the authors to modify (in real time) the robot behavior depending on the user position, without limiting the operative robot workspace. In the works of Hietanen et al. [140], the authors presented a combined approach of an augmented reality interface and a computation model of the shared workspace for collaborative manufacturing. The model allows the user to monitor changes in the workspace, establishing safety features.

In addition, Schoose et al. [141] used an HRC grinding activity to characterize the differences in the biomechanical dimension of gestures for HRC grinding activities. Their analysis focused on effort and vibrations perceived by the grinders as well as the repetitiveness and the postures adopted in the gestures performed by them when grinding with a manual grinder (traditional grinding) and with a Cobot. The aim was to reduce potential MSDs. Petrovic et al. [142] proposed an approach using vision systems and electromyography of muscles and a Franka robot, which showed potential to enhance ergonomics for safe HRC collaboration in an industrial environment. Li et al. [143] developed a wood sanding HRC bench for safety and efficient working. A double-armed system was used for sanding and dust collection. Force feed sensors on the arm ensured safe collaborative operation. A dust absorption device was installed at the end of the arm for lowering the environmental pollution. In the South Korean manufacturing environment, Jung and Yang [144] highlighted the importance of a socio-technical systems perspective to address the complex interactions between collaborative robots, human factors, and organizational dynamics in workplace safety. They also emphasized that the use of a skilled workforce would also reduce human–robot accidents.

The efforts regarding the safety of HRC for finishing operations are listed in Table 5.

Table 5. Works on safety issues in HRC.

Paper	Main Topics
Vido and Pancchini [136]	A conceptual safety system architecture for a HRC, especially covering safety requirements during the early design stage.
Su et al. [96]	Identifying the regions in which the operator and the robot do not collide with through tracking the operator's motion and modifying the grinding trajectory according to prediction.
Wang et al. [138]	Detecting and tracking the pose of the operator using RGB camera, mostly based on RGB-D.
Magrini et al. [139]	Online monitoring of relative human–robot distance using depth sensors and modifying the robot behavior on the user position based on a layered control architecture.
Hietanen et al. [140]	A computation model allowing the user to monitor changes in the workspace through an AR interface to establish safety.
Schoose et al. [141]	Study on vibrations, repetitiveness, and the postures of the operator for grinding in order to reduce potential MSDs.
Petrovic et al. [142]	An approach to enhance ergonomics for safe HRC using vision systems and electromyography of muscles.
Li et al. [143]	A wood sanding HRC for safety with force feed sensors and dust collection.
Jung and Yang [144]	Highlight of the importance of a socio-technical system perspective to address the complex interactions between collaborative robots, human factors, and organizational dynamics in workplace safety.

3. Discussions and Future Directions

So far in this article we have shown that most of the research in the field of collaborative robotic finishing focuses on fine-grade abrasive polishing, primarily from the robot's perspective. However, there has been a shift in recent studies to acknowledge the importance of human factors in these processes. Despite this, control and safety remain the predominant concerns in the majority of the research. Meanwhile, as shown in Figure 2, there are three overarching operation modes for HRC: Coexistence (i.e., Figure 2b), meaning the robot and human share the same workspace without guarding, but operating on different tasks; Cooperative (i.e., Figure 2c), meaning the robot and human perform the same operation in the same workspace but at separate times; and Collaborative (i.e., Figure 2d), meaning robots and humans work seamlessly together (i.e., same operation, same workspace, and same time). What can be seen from the most recent works is that true collaborative robotic setups are still limited. Instead, most research continues to emphasize supporting coexistence or cooperative approaches. Thus, greater investigations from human perspectives are still needed, and research from the robot perspective and the specific technologies for the movement towards truly collaborative manufacture is required. Meanwhile, various advanced technologies are developing much faster today than ever, such as new manufacturing technologies, high-precision sensors, optimization techniques, AI, Cloud, etc. The latest technological innovations will have an unavoidable impact and bring changes for the Cobotics in the area finishing operations. Overall, future proofing is all about designing and developing it in a way that anticipates growth, evolution, and technological advancements, ensuring it remains adaptable, maintainable, and relevant over time. The following sections identify issues that should be either used as guidelines or addressed with future research.

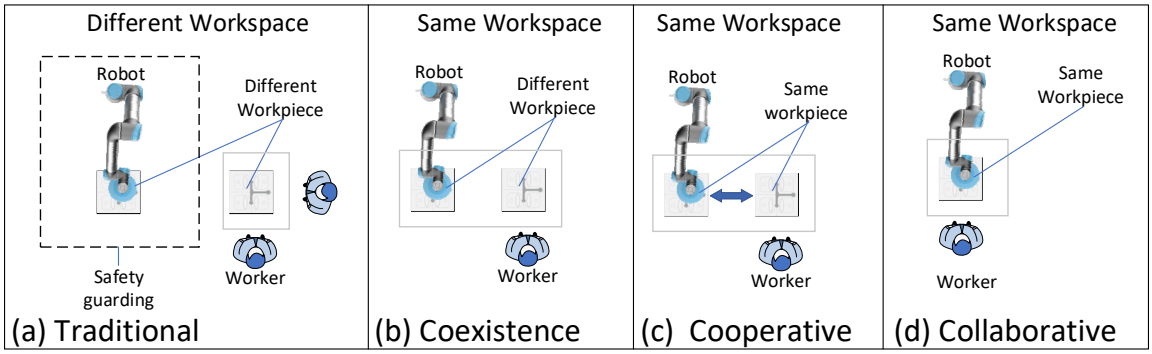


Figure 2. Robot–human operation modes.

3.1. Rapid Prototyping and Wider Additive Layer Manufacturing Technologies

The adoption of additive layer manufacturing (ALM) to the arsenal of manufacturing processes has provided engineers with a rapid technology for the manufacture of components. One example component that requires a large degree of finishing is molds [145]. Advances in additive manufacturing, hybrid manufacturing techniques (combining additive and subtractive methods), and material science are continuing to enhance rapid tool manufacture (RTM) capabilities, making them even more accessible, efficient, and versatile for industries requiring rapid, adaptable tooling solutions. The global mold manufacturing market was worth USD 23.62 billion in 2022 and is predicted to reach USD 70.42 billion by the year 2029 [146]. While the core manufacturing process has been sped up, the need for polishing has not been removed. It has been noted that 20% of the cost and 50% of the overall time is consumed by finishing [69]. As such rapid dies (made from plastics) are seen as a growth area, research such as that by Kuo et al. [147] looks at a vapor polishing mechanism for this material, which is created by additive manufacturing, but some fine

abrasive polishing is needed. Working from other perspectives, in Whitmore [148], a small vibrational polishing machine (MiniViP) was developed to produce superior quality and damage-free surfaces and constructed from parts produced using additive layer manufacturing. By incorporating robotic polishing into RTM processes, manufacturers gain speed, quality, and consistency in the finishing stages, critical for delivering high-quality tools quickly. The automation, adaptability to complex shapes, and material versatility provided by robotic polishing make it a valuable asset in reducing the overall time and cost associated with tool manufacturing. In the long term, it is likely that this will also be collaborative activity which needs exploring. It is also expected that other artefacts, mass produced using additive processes, will also need an array of finishing processes.

3.2. Integrated Multi-Robot Collaborative System

The future market trend is product personalization and the constant changing customer demands, which is driving the HRC to be more efficient, scalable, and resilient. On the one hand, to rapidly respond to customer requirements, it is necessary that HRC and the CAD/CAM system share the information seamlessly in such dynamic production environments. Wang et al. [111] addressed the gap between the robotic polishing and current CAD/CAM systems and presented a methodology aiming for robotic polishing to achieve information integration with current CAD/CAM systems. Despite that, the research on the information integration of HRC to CAD/CAM and the downstream tasks is still limited. Further investigations are needed in the future.

Meanwhile, there is a need to build Cobot systems/production lines with scalability in mind so the application can manage increased load associated with the increased coexistence of robots and humans. This could potentially be achieved by using modular design patterns to keep components independent and decoupled. This potentially makes it easier to upgrade, replace, or extend individual parts of the application without disrupting the entire system. Within the current employed Cobots, some robots are being built with the open-source approach (e.g., SPEEDY 6 MABI robot [149] and BAXTER [150]), which should allow for more options when deciding what pieces to use for a new system [151]; some robots have bespoke programming/control language, such as PolyScope for UR5/UR10 [114,152,153]; bespoke software for NEXTAGE robot [154]; and RobotWare for ABB's YuMi collaborative robot [155,156]. For these robots, software around APIs (Application Programming Interfaces) needs to be designed that allows for easier integration with future technologies and services. Obviously, it is necessary to establish unified open coding standards and practices so as to make code more readable and maintainable. Such standards will also benefit online solutions for Cobot applications. It can be seen that there are an increasing number of companies offering online services for Cobotics recently, such as OnRobot [157], providing end-of-arm tooling and software for Cobot applications, the FANUC "Cobot and Go" web tool [158] for searching pre-engineered Cobot solutions, etc.

On the other hand, as noted by Ke et al. [35], multi-robot collaborative polishing can be considered in the future to improve the throughput of a polishing system. It leads to two challenges for HRC: (1) Task planning and allocation among multiple resources, which might include multiple robots (stationary or mobile) and quite a few operators; (2) integration with the whole production scheduling and even floor planning for better efficiency. The study on collaborative processes in robot and human work is required. There are various algorithms and decision support systems for task planning and allocation in hybrid and collaborative work cells [112], but optimizing the allocation of finishing tasks for collaborative robots and humans still needs to be explored. It is possible to learn from some similar works. For example, the work of Dalle-Mura and Dini [159], where the authors develop a tool based on a genetic algorithm to configure assembly lines

for humans and collaborative robots. The obtained results demonstrate the capability of the system to simultaneously reduce the cost of the line and the energy load variance among workers, optimizing the allocation of collaborative robots, other equipment, but also achieving an efficient assignment of humans to stations, according to their technical skills. Another example is in [160], where the author investigated the challenges of production scheduling collaborative robots, employing constraint programming and a dual-stage genetic algorithm for a robot-assisted flow shop type of production setup.

Methods using simulation show another direction in the future. Simulations should be used to evaluate various Cobotic setups and configurations in order to determine the most effective layout for utilizing both human and robotic optimal attributes. To combat underutilization of the Cobot and inefficient work cell design, for grinding operations, Raza et al. [161] used a simulation based on the classical problem-solving Deming cycle [162], Plan-Do-Check-Act. The "budget" approach was targeted for small to medium enterprises to increase the economic feasibility of HRC for such companies. The work used Siemens Tecnomatix Process Simulate software (https://plm.sw.siemens.com/en-US/tecnomatix/, accessed on 8 June 2025) and a Universal robot's system. Paulo et al. [163] proposed an approach combining a two-level mixed integer linear program (MILP) model with a detailed discrete-event simulation model of an assembly layout design, enabling the assessment of the process dynamics to allow for operation optimization. This could extend to the study of scenario planning and simulation-based training. In order to improve productivity and readiness for robot interactions, this would enable employees to practice in a virtual setting and prepare for different production scenarios.

3.3. Safety in Robotics Finishing Operations

To reduce the possibility of mishaps, injuries, and musculoskeletal diseases, the design must make sure that the workspace is safe and ergonomic for both humans and Cobots [8,47]. Enhancing the safety in robotics finishing is a real challenge for the near future, both from the perspective of techniques and standards/regulations.

Although some work on Cobotic safety has been conducted (as reviewed in Section 2.4), the outcomes are still limited and further work is required. One of key issues is how Cobots perceive their environment and adapt their movement in real time to avoid human–robot collision. It depends on (1) advanced sensors and better vision recognition technology to detect operators, objects, and potential hazards and (2) efficient algorithms and controllers to adjust the Cobots based on real-time data to avoid collisions. AI technology (e.g., machine learning and problem solving) could play a crucial role in the near future to ensure safe collaboration, such as analyzing real-time data, identifying potential issues, changing Cobot's path for collision avoidance, predicting safe speed and force output to prevent operators' injuries, etc.

Another direction of research could follow the work of Kousi et al. [164]. The authors used a Digital Twin (DT) and human–robot combined with information from the virtual shop floor for process improvement. A Digital Twin virtual replica of a real-world artefact is used throughout the whole life cycle of the entity it replicates [165]. The virtual world model and the data from the physical world can be utilized to adapt the behavior of human–robot collaboration to cope with varying production volumes. The works of Kousi et al. [164] and Zanchetti et al. [6] showed that DT can support the development of HRC systems and planning through running multiple scenarios in a virtual environment. But, as noted by Ramasubramanian [166], there is much wider future potential for the DT to develop more reliable and safe collaborative scenarios and to assess the configuration from the human viewpoint. Therefore, there is need for research into the creation of real-time digital replicas/twins of manufacturing systems that can simulate, predict, and optimize processes

before changes are implemented in the physical environment, potentially reducing the risk of human robot clashes within the workspace.

On the other hand, many of the Cobots with proprietary safety systems such as the Comau robots are equipped with tactile sensors to detect contact [167]; for example, the APAS system has smart capacitive skin that detects the proximity of a human and stops before contact [168]. While such systems may stop the physical injuries of contact [126] at workspace level, manufacturers must follow existing and developing national and international standards for the work around collaborative finishing operations to be conducted safely. Figure 3 presents current safety standards applied for collaborative robotics. It includes not only the standards providing fundamental machine and design aspects and risk assessments (such as IEC 61508 [169], ISO 14121 [170], and ISO 12100 [171]), but also the standards specific to technologies associated with specific systems/machines, such as ISO 13849 [172], IEC 62061:2005 [173], and more specific standards for robot integration, industrial requirements, and guidance for collaborative robot operation where a robotic system and people share the same workspace (i.e., ISO 11161 [174], ISO 10218 [175,176], and ISO/TS 15066 [177]). However, as Berx et al. [178] stated, the paradox of information of robot safety and perceived "overly safe" situations were deemed to impede effective operations. This is found to be lowering the adoption rate of Cobots into production operations. This could be overcome by wider research into safety protocols and testing methods to ensure that robots perform safely and predictably, and also by the wider development of new regulatory policies and standards for integrating robotics into manufacturing setup.

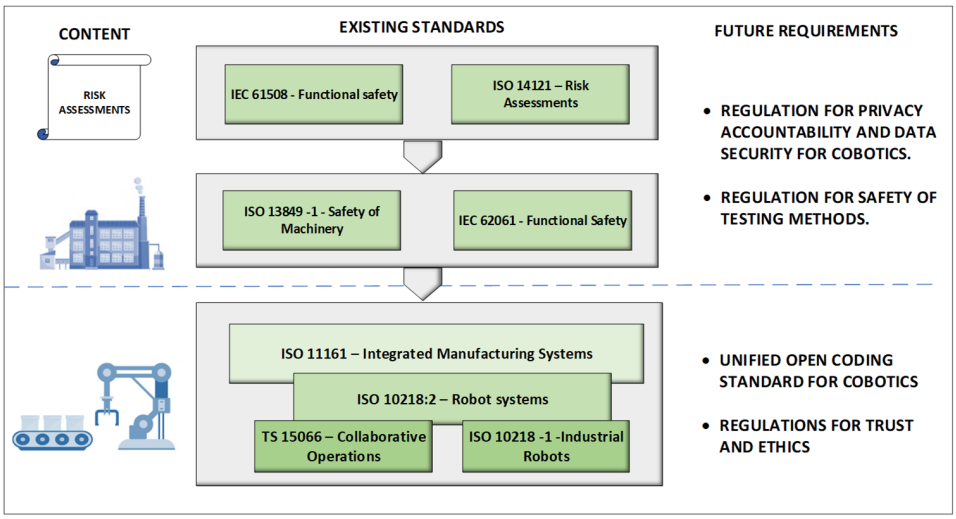


Figure 3. Safety standards for robotic systems.

Furthermore, employing a Cobot should not generate additional efforts or cause new situations with the risk of the human sustaining injuries [179]. The future technology developments, such as the introduction of AI, not only provide opportunities for improvement of HRC, but also present new challenges for HRC applications. There is still a need to explore the issues of trust and ethics (e.g., any ethical considerations of such interactions) in HRC and study how to build and maintain human trust in robots within the manufacturing environment. Meanwhile, work on improving the robots' abilities to interpret human emotions, motions, gestures, and social cues for smoother interactions, such as the work of Xue et al. [180], needs to be expanded. At the same time, more important regulations are required to ensure safety and build trust, such as set boundaries for AI use in Cobotics in the future. In addition, planning for the Cloud and Containerization, building software with the cloud in mind to leverage cloud services, scalability, and flexibility, regulations for the issues like privacy, accountability, and data security are required for Cobotics.

Combining the discussions in Section 3.2, Figure 3 presents an image of the possible new standards/regulations for collaborative robotics in the future.

3.4. Towards Fully Automated System

Although a collaborative robot is used, the end goal is a fully automated system. As noted a few times during this review, there is also a large volume of research where the goal is to fully automate the finishing process and its quality control (e.g., [29,100,181]). Some researchers are seeing the benefits of the new series of Cobots and employing them as the form of automation [57,182] rather than their industrial robot counterparts.

When it comes to collaborative robots, researchers frequently look for the workpiece's ideal kinematic placement to either guarantee that the task can be completed by the robot as quickly as possible while staying within its maximum kinematic capabilities [183] or to find the best workpiece placement that minimizes joint torques [184]. An example is the work of Balci et al. [184]. A non-linear optimization-based algorithm was applied. A different way was proposed in the work by Malhan et al. [183], which presented an approach to design a robotic cell for the sheet layup process. The appropriate robot placements were identified considering the robot workspace, singularity, and speed. Study on configuration properties of industrial robots, their placement, and corresponding optimized strategy is an interesting topic for the future.

From the physical side of the finishing processes, a frequent problem relying on data-driven models for setting the finishing parameters is the issues of under-polishing or buffing. A recent review by Pedrosa et al. [185] provided an overview of compensation methods used in robotic machining. Meanwhile, there will always be some form of dependence on high-precision sensors to feed back force and pressure information as the finishing process progresses. Although leading to complex control systems, many of the operational problems can be solved by appropriate end-effector design [186]. With Cobotic systems in place, research will be required to create algorithms that automatically tune parameters for optimal performance without manual intervention, useful for complex or variable finishing processes. This can lead to the needs for the use of reinforcement learning and online learning techniques that allow robots and manufacturing systems to adapt their optimization strategies continuously based on real-time feedback while considering the human.

While with HRC the checking of surface texture/roughness against requirements can be an activity that the human undertakes, with a fully automated process, the robot system will need to assess whether the polishing process is complete. Over-polishing or grinding can lead to a scrapped product. There are some works related to process quality checking of product surface texture/finish [187] and machine position [188]. For Cobotics, Pini and Leali [79] presented a human–robot collaborative approach for surface polishing processes that integrated state-of-the-art robot-based polishing and surface quality assessment technologies in a human-safe shared working environment. The authors produced a protype platform to evaluate human–robot collaboration scenarios and quality assessment of the finished product. The authors further extended their AR approach in Ferraguti et al. [78] to the surface finish of the component under polishing. This allowed the end-user and the operator to directly see whether the part quality satisfies the specifications or whether some parts of the surface require further refinement through additional polishing steps. Current work on process quality is obviously not enough; greater effort is needed to find an effective real-time system that could fully solve quality issues, such as exploring the concept of AI-powered computer vision system for a real-time monitor for surface quality, defect identification, and failure prediction.

Overall, Table 6 and Figure 4 give an overview for the potential future research areas of HRC in finishing operations.

Table 6. Potential future research directions.

Industrial Demands	Future Research Directions	Supporting Technologies
New manufacturing technologies emerging	Integrated ALM/RTM process	Additive layer manufacture
		Rapid tool manufacture
Product personalization	Integrated multi-robot collaborative system	CAD/CAM
Trend to multi-robot collaboration		Simulation
Scalability of Cobot systems	Unified open coding standards	Cobot properties, Cloud
Enhancing safety	New standards/regulations	
	Real-time Cobot behavior adaptation	Vision recognition, AI, DT
Toward fully automated system	Cobot configuration properties	Optimization algorithms, AI, high-precision sensors, AR
	Real-time performance control	
	Online quality assessment	

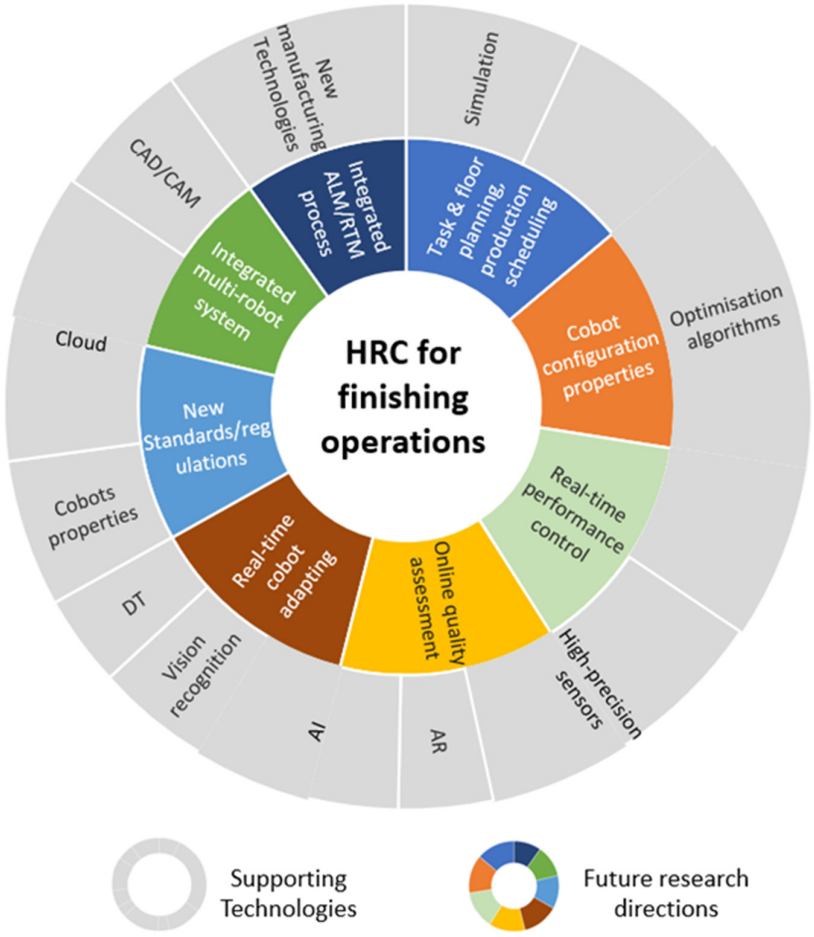


Figure 4. Overview of future research for HRC finishing operations.

4. Conclusions

Cobotics will be the main practice in the manufacturing environment in the coming years, exploiting the main benefits of human and robotics characteristics. Recent works on HRC for finishing operations are reviewed in regard to four aspects: operation parameter

setting and control, tool path planning and trajectory generation, human factors, and frameworks for Cobotic safety. It is shown that the critical role of human in a Cobotic system has gained increasing attention in the era of Industry 4.0. There are some works related to human health and safety in HRC and the human–robot cooperation within the process. However, what is evident from the reviewed materials is that the main focus of the literature has been the robotic perspective, such as the control, tooling, and motion of the robot(s), which is potentially providing a barrier to quicker adoption. In addition, while recent advancements show a trend towards collaborative robotics, recent research predominantly concentrates on coexistence or cooperative approaches rather than achieving true, seamless human–robot collaboration. Therefore, one of the future research directions should focus further on the human perspective, like improving safety in the human–robot collaborative process, integrating high-level tasks planning, etc. In addition, there is increasing demand for future robotic finishing to incorporate new advanced technologies, such as new manufacturing approaches, simulations, Digital Twin (DT) and AI, etc., for greater efficiency and scalability. Based on this, four future directions for Cobotics in finishing operation are discussed, including rapid prototyping and wider additive layer manufacturing technologies, integrated multi-robot collaborative system, safety in robotics finishing operations, and progression towards a fully automated system. Following these directions would make future Cobotic operation in production more adaptive, safe, efficient, scalable, and responsive to dynamic industrial needs. Advances in these areas could greatly enhance productivity, customization, and sustainability in manufacturing.

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List of Abbreviations

ALM	Additive Layer Manufacture
AHP	Analytic Hierarchy Process
APIs	Application Programming Interfaces
AR	Augmented Reality
DT	Digital Twin
FFT	Fast Fourier Transforms
HRC	Human Robotic Collaboration
MILP	Mixed Integer Linear Program
MSD	Musculoskeletal Disease
NURBS	Non-Uniform Rational B-Spline
ROS	Robot Operating System
PbD	Programming by Demonstration
RTM	Rapid Tool Manufacture
SMC	Sliding Mode Control

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